Preparing to Assure Mission Success

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Space flight missions are inherently risky. The mission operations assurance discipline grew out of strategies to control error and evolved into what today is an independent technical authority dedicated to achieving mission success. After the Mars Climate Orbiter loss, NASA made a set of recommendations for missions. Two of those recommendations led to the creation of today's Mission Operations Assurance Manager role: (1) require an independent Mission Assurance representative during the operational phase of every flight project, and (2) require all flight projects to report and track post-launch anomalies. Since then, the MOAM role has been continually refined by lessons learned from its practice on more than 20 concurrent missions. The MOAM role requires significant operations experience as well as an additional set of skills. In the interests of developing a cadre of potential MOAMs, the MOAM training program was developed. It is a 14-unit set of presentations/discussions covering the 11 categories of MOAM tasks. It is offered to new MOAMs and interested systems engineers with an eye to preparing both types of personnel for present and future assignments, as well as building relationships among personnel of different organizations. MOAM training sessions include presentations on the various tools and processes employed by MOAMs, interspersed with mindset lessons illustrated via "war story" discussions of previous missions.

I. Introduction

Space flight missions are inherently risky. From the material of the smallest nuts and bolts, to the attentiveness of an engineer monitoring a test, even to the mood of the nation on launch day, many factors can affect the success of a mission. Missions are built to be as reliable as possible, but cost, schedule, and lack of information or experience mean that some problems will not be prevented. There will always be unknowns, and in addition to the many things that can go wrong with spacecraft, humans are human - mistakes will be made.

In the early days of spaceflight, missions were less capable but risk was high due to untried hardware, poorly understood environments, and inexperienced flight teams performing first-time activities. Testing and rehearsals on the ground helped to avoid some of the errors, but there was still so much we did not know. As the number of missions increased, it became easier to analyze failures, reproduce successful strategies, and see trends among missions. System engineers and operators took their experience and insight from mission to mission, leading to the development of "rules of the road" for design, test, and operations.

The mission operations assurance discipline grew out of such strategies, and evolved into what today is an independent technical authority dedicated to achieving mission success. From flight project integration through the end of the mission, the Mission Operations Assurance Manager (MOAM) makes certain that the operations safety and mission assurance program is properly carried out, and that independent risk assessments of technical concerns are regularly performed and reported to project and mission success management.

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II. History

Mission assurance in flight began as a response to operational errors. It is a continuation of the JPL mission assurance program as the project transitions from development to flight operations. The Mission Operations Assurance Manager (MOAM) carries out the safety and mission assurance role post-launch, with emphasis shifting from build, test, and launch to operational risk and flight team performance.

Before MOAMs, projects employed several narrowly defined roles that covered portions of the MOAM scope. These included command assurance, anomaly reporting and tracking, and software quality assurance. There was little standardization from mission to mission, leaving gaps in roles, and some tasks were wholly neglected. With the advent of more complex spacecraft and concurrent missions, the number and severity of errors increased as did the range of possible risks.

JPL is a pioneer in the mission assurance for operations area. The Voyager mission, whose two spacecraft were launched toward the outer planets in 1977, started by capturing in-flight anomalies on a standardized paper form. Anyone on the project could write a report, called an Incident/Surprise/Anomaly (ISA) Report, and the reports were then allocated to the various operations team chiefs to resolve and close. There was an operations engineer whose job duties included tracking the ISAs and making sure that they were properly recorded and justified for closure by the operations teams.

In the 1980's, the Magellan mission expanded that role to one called Mission Operations and Command Assurance (MOCA.) This role was handled as a software quality assurance role and was managed under that organization. The role included both operational error tracking and ensuring that anything uplinked to the spacecraft was as intended. During the late 1980s, the MOCA function moved into the Mission Assurance organization. That organization had, by that time, developed independent reporting paths to maintain proper mission assurance discipline, that is, mission assurance personnel worked *with* project personnel, but not *for* them. In this change, a new culture for MOCA was set. It became independent of, but responsive to, the project chain of command. Also, at this time the Galileo mission assurance manager for operations began keeping command error statistics for all JPL projects. Though most projects had a MOAM, each project's acceptance of the role varied, and therefore so did its effectiveness.

As the "faster, better, cheaper" missions of the 1990s took on more risk, deficiencies in integration and test, operations, and risk management resulted in the loss of the Mars Climate Orbiter (MCO) mission. This brought a new focus on Mission Operations Assurance by NASA and JPL. MCO's loss was particularly egregious in that there were several opportunities to catch and fix the errors, but due to a variety of factors, they were not caught. The MCO Mishap Investigation Board, in its final report [1,2], provided two recommendations specifically related to Mission Operations Assurance:

1. Revise JPL mission assurance policies and procedures to require an *independent* Mission Assurance representative during the operational phase of every flight project.
2. Require *all* flight projects to report and track post-launch anomalies on ISAs. Project management should rigidly enforce this requirement and maintain a disciplined disposition, tracking, and resolution process.

As a direct result of the MCO failure and subsequent mishap investigation board recommendations, renewed emphasis was placed on the mission operations assurance function of the Stardust mission. For the earth return portion of the mission, a full time Mission Operations Assurance Manager (MOAM) was assigned. The MOAM role expanded to include performing independent risk review and assessment, approving problem report and waiver resolution, participating in flight team tests and rehearsals, and performing risk balance trades on significant mission alternatives. The role of the MOAM continues to evolve to this day as we encounter additional challenges in mission operations.

III. Role and General Background

The Mission Operations Assurance Manager (MOAM) role is a senior leadership position, requiring certain skills as well as significant operations experience. Skills can be trained, but experience takes time and the MOAM role is one that cannot simply be "taught" to new hires. Operations experience is necessary to be able to judge the types of problems that arise, and to understand the overall rhythm of and risks in operations.

It is anecdotally understood that an operator is not considered to be fully "experienced" until at least their third or fourth mission supported. The first mission is for learning, the second and third provide comparison, and the fourth completes a framework for the accumulated knowledge. Since space mission domains are varied, a fully capable operator will need to learn the challenges of each domain. Most operations work at JPL can be grouped into 3 domains: deep space missions, earth orbiters, and landers/rovers. Experience in all three would make for the most capable MOAM candidate, but that is rare. Instead what is common is that candidates have 15-20 years of experience in day-to-day operations, including one or more leadership roles, in one, or preferably two, of the domains.

Operations leadership roles have significant training programs of their own, so a MOAM starts with a considerable set of skills and knowledge. Until recently, for the first few months on the job, each MOAM was given a training partner, usually their predecessor or the MOAM lead, to ensure that they are ready to perform their day-to-day mission-specific duties.

This system worked well for some time, but in the last few years it became less effective due to conflicting staffing needs and schedules. In addition, the most senior MOAMs approached retirement, risking the loss of deep historical knowledge and experience. To capture their knowledge and transmit it to future MOAMs, the group undertook to create a training program for new MOAMs, as well as for possible future hires from the system engineering ranks. This cross-organizational training is particularly helpful in that, whether the system engineer is later hired to be a MOAM or not, they come away with a better understanding of the value and role of mission ops assurance, and are better prepared for future assignments.

The training program has been developed to be a mix of stand-up presentations/discussions, tool demonstrations, "war stories" from senior personnel both in and out of the MOAM organization, and finally case studies to check on the trainees' understanding of the presented principles. There are currently 14 modules, some of which have been recorded, and a list of required reading.

IV. Module 1: Introduction to Mission Operations Assurance

When the MCO Mishap Investigation Board made its recommendations, NASA took them very seriously. From 1999 on, mission assurance policies and procedures were revised to require an independent Mission Assurance representative during the operational phase of every flight project. As part of that revision, all flight projects are required to report and track post-launch anomalies on ISAs.

From there, the Office of Safety and Mission Assurance developed a Mission Operations Assurance Vision, which is: "to integrate the Mission Operations Assurance function into flight operations, providing value-added support in identifying, mitigating, and communicating the project's risks along with being an essential member of the team during test activities, training exercises, and flight operations." Each new mission would tailor its MOA program depending on the project's development category and risk classification. The MOAM role was described and implemented as a set of well-defined tasks in 11 categories. The 11 categories are:

1. Risk assessment, which includes capturing the residual mission risks as the project transfers from the development to the operational phase of the mission, assessing residual risks throughout the post-launch risk review process and integrating them into an overall risk assessment, and providing an independent assessment of the Project's risk posture in preparation for critical events and when resolving in-flight anomalies.
3. Operational Readiness includes participating in Operational Readiness Tests to assess if test objectives were met, and ensuring that any remaining concerns and actions are identified, tracked, and resolved.
4. Problem Reporting includes managing the problem/failure reporting system for flight operations including system setup as well as the initiation, processing, and closeout of operational Incident/Surprise/Anomaly reports (ISAs), and the analysis, resolution, and tracking of command file errors.
5. Operations Training includes overseeing/conducting the problem/failure reporting function training for the flight team, and assessing the adequacy of flight operations team position training and the overall system-level flight team training program.
6. Operational Requirements includes working with other project leads to ensure operational requirements are implemented into the flight hardware, software, and operations design, and participation in operations peer reviews and the Operational Readiness Review to assess resolution of integration questions between development and operations.
7. Project Planning includes assessing Mission Change Requests to ensure appropriate review has been completed, and providing an independent risk assessment, as appropriate.
8. Flight Rule Assessment includes analyzing and reviewing waivers to flight rules and making approval and risk recommendations to the project.
9. Reporting includes briefing independent risk assessments at monthly management reviews, JPL and NASA reviews, and Critical Events Readiness Reviews. It may also include monitoring the space weather environment for launch hold criteria as well as its impact on flight operations post-launch, and subsequent anomaly investigations.
10. Configuration Management includes actively participating in the change control process and continually evaluating compliance with the process.

11. Interfacing with other Quality/Operations Assurance Functions includes coordinating software quality assurance support for in-flight software development/modification, the resolution of flight software anomalies, and coordinating with industry partners to ensure an integrated mission operations assurance program is in place.
12. Lessons Learned Assessment includes investigating problems, anomalies and idiosyncrasies discovered on one JPL mission for applicability to other JPL missions, and ensuring that appropriate problem reports are generated on other projects where applicable.

From these 11 categories came a set of specific tasks and interactions that are performed by mission operations assurance personnel, from tailoring and documenting each mission's MOA Plan and participating in operator training and certification before launch, to analyzing, tracking, and risk-assessing anomaly reports, and supporting decommissioning reviews and end-of-mission activities. An idea of the formal MOA deliverables in the NASA Phase A-F lifecycle is shown in Figure 1 below.

MOAM Training Module 1 includes presentations on the introductory material above, the MCO loss of mission findings [2,3], and a testimonial from a project manager on how mission assurance has helped his project. It also includes a list of required reading and where to find it.

NASA Phase	**IMPLEMENTATION**			
Project Life Cycle Phases	**Phase D**	**Phase D to E Transition**	**Phase E**	**Phase F**
Manage Mission Assurance Process Procedural Activities	• Tailor and finalize the MOA Plan • Setup, manage and train the implementation of the ISA system. • Brief the flight team, as part of the test and training activity, on the implementation of the MOA program • Participate and independently assess the pre-launch ORTs and flight team readiness. • Provide ISA risk assessments and flight team readiness assessments to the MAM for inclusion in the pre-launch readiness reviews. • Attend the prelaunch Safety and Mission Success Review (SMSR) to capture the residual operational risks going into phase E.	• Provide MOA assessment of flight team readiness to the MAM during launch countdown operations. • Participate in the early operations checkout of the spacecraft and instruments in preparation for the Post-Launch Assessment Review (PLAR). • Works with the MAM in preparing and presenting the MOA portion of the PLAR. The PLAR is normally the transition point where the MOAM takes over from the MAM.	• Provides risk balance trades in support of key project operational decisions. • Supports the development of specific flight team training in preparation for upcoming flight operations. • Develops and presents at Critical Event Readiness Reviews (CERRs) and extended mission readiness reviews a comprehensive and independent risk and readiness assessment.	• Develops and presents at the decommissioning review an independent risk and readiness assessment for the project to proceed with the activity. • Provides input to the Project's decommissioning review/report.

Fig. 1 MOA Lifecycle Engagement

V. Module 2: Mission Operations Assurance Manager

Once the discipline of Mission Operations Assurance is understood, the next step is to understand how a Mission Operations Assurance Manager (MOAM) performs their job. First, there is a mindset that is necessary to properly carry out the duties of a MOAM. This mindset has three parts:

1. Rigor - that all required products are complete, communicated, and correct;
2. Penetration - asking questions until satisfied with the answer; and
3. Follow-through - disciplined and steady attention to the successful completion of assigned tasks and the thorough resolution of problems.

All MOAM tasks and interactions must operate under these three principles.

Next, one needs an understanding of what a MOAM "does", in a general sense. Day to day, the MOAM identifies, assesses, mitigates, and communicates project risks. To do this, they must work closely with the team to be aware of and assess risks that can threaten mission success, and continually look across all project elements when identifying those risks. And crucially, the MOAM must guard against going "native" - that is, becoming too fixated on the daily details of the mission and losing their independent view of the risks. Each project's MOA Plan is written to capture the specific tasks performed by that project's MOAM in the accomplishment of their responsibilities.

In addition to the 11 Mission Operations Assurance items described above, the MOAM may need to assist with several other items on an irregular basis. These include supporting in-flight anomaly resolution as a member of the Anomaly Response Team, participating in extended mission or end-of-mission reviews, ongoing training of project staff and the flight team on MOA processes, mission operations assurance oversight of academic and industrial partners, software quality assurance, and institutional and NASA waivers.

Training Module 2 includes the description above as well as a high-level view of each of the major tasks performed by the MOAM, which are detailed in subsequent modules.

VI. Module 3: Incident/Surprise/Anomaly Reports

A critical part of the MOAM role, and one that is fundamental to it, is handling Incident/Surprise/Anomaly Reports (ISAs.) ISAs document events that occur within the flight and ground systems using JPL's institutional Problem Reporting System (PRS.) ISAs are written to ensure that problems are not neglected and re-encountered in the future. The formal ISA process is used to manage the risk inherent in each ISA. MOAMs ensure that ISAs are properly analyzed, resolved, documented, and closed and any residual risk has been assessed, an important part of the ISA process.

Incidents that trigger the creation of an ISA include events observed by the flight team on flight/ground hardware, flight/ground software, and test or operational processes and procedures. They are initiated on events indicating unexpected performance of the ground system, flight system, or flight team. Sometimes events that are very minor, very routine, or completely benign happen and it is unclear whether to write an ISA. A few examples of when ISAs do not need to be written include occasional network outages, workstation failures, or ground software problems not directly associated with commanding or monitoring the spacecraft. However, in any of these cases an ISA *should* be written if the frequency or impact rises above routine expectation. In the end, the overarching rule is: "When in doubt, write an ISA".

Once a flight team member writes an ISA, the MOAM determines the criticality rating, assigns it to a responsible editor, and coordinates a planned closure date. Criticality is rated with numbers 1 through 3, where 1 represents *major* impact or threat to achieving mission success, 2 represents *significant* impact or threat to achieving mission success, and 3 represents *negligible* impact or threat to achieving mission success. The responsible editor, with help from the team and the MOAM, resolves the problem and writes up the closure material. The MOAM is then responsible for ensuring that the ISA closure addresses the problem in its entirety and captures the state of any residual risk in terms of Proximate Cause (the direct, immediate cause), Root Cause (the underlying cause of the problem), and Contributing Causes (other factors contributing to the problem.) As ISAs are resolved and closed in PRS, the mission accumulates a readily-searchable database capturing its anomaly history.

A. ISA Statistical Analyses

By studying the statistics of ISA creation and closure for 20 missions over two decades, some general trends have emerged. ISAs accumulate quickly after launch, as the team learns the processes and spacecraft in actual operations. This often leads to a backlog of open ISAs, as early on, ISA closure takes a lower priority than day-to-day operational activities. As post-launch activity and problem discovery slow down, ISAs are written at a gradually decreasing rate and more time is available to close ISAs. Eventually, the monthly opened vs. closed ratio stabilizes and slowly decreases as the project works off the ISA backlog. Most medium-to-large projects follow the general ISA trends shown in Figure 2 below.

Ideally, the flight team closes ISAs at the same rate as they are written. This represents the long-term ISA goal of the MOAM - all projects should strive to get to this regime as quickly as possible. From the statistical analyses, we can also predict how long it would take a project to work off the ISA backlog. This allows a project to show realistic progress toward that goal over time and informs management how the team is doing eliminating the backlog. If a project/team cannot demonstrate progress against the backlog, then that means they are accepting more risk, which is also useful information.

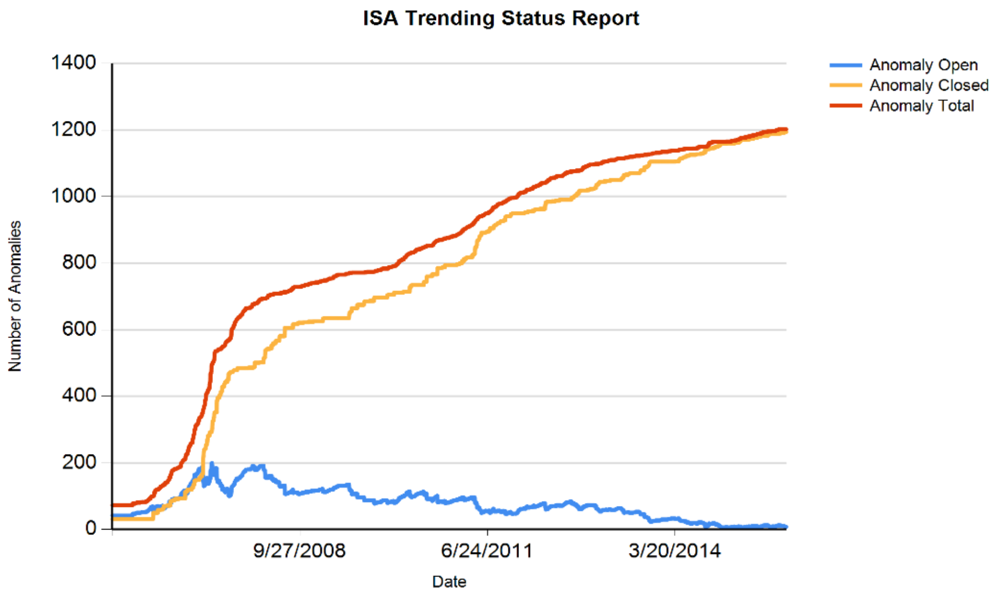

Fig. 2 ISA Trending Status Report

The analysis of the ISA database led to insight about ISA populations, which can be equated to risk. It is useful for a project to assess how many open ISAs may be too many. That assessment depends on which ISA regime the project is experiencing, how well the team is executing ISA closures, and how much backlog the project is carrying. Only the project can determine if the number open is too risky or is reasonable based on conditions. ISA metrics can help to provide a meaningful answer. If the project concludes that the number of open ISAs is excessive, they must improve the closure rate, and the MOAM will need to develop a realistic, quantitative reduction plan with the project.

Training Module 3 provides a detailed discussion of ISAs and their statistical analyses illustrated by examples from flying missions. It also includes a brief section on how to set up the PRS for a new mission, and an example of an uncaught commanding error.

VII. Module 4: Command File Errors

One of the most significant reasons to write an ISA is that there has been a Command File Error (CFE.) A CFE has occurred when the flight system state differs from the desired or expected state due to ground interaction. These errors can cause transitions to safe mode, damage instruments, and even end missions. Command file errors belong to a special category of anomaly and the following factors are used to determine if a CFE has occurred:

- A CFE can result from an erroneous uplink or a failed uplink, including an omission.
- A CFE may be caused by an error in the processing, approval, or uplink of a product to the spacecraft.
- A CFE may be caused by an error in requirements, design or coding in the ground or simulation software, or by an error in post-launch flight software requirements, design, or coding.
- A CFE may be caused by a configuration management problem on the spacecraft or ground.
- A CFE may be caused by an error at the tracking facility that prevents uplink of the file.

Other factors may seem to influence CFEs, but they do not affect the determination of whether a CFE has occurred, though they may have bearing on the severity of the outcome of the error. These factors include: what type of uplink product or file caused the error, if the erroneous spacecraft state is benign, and if the error was found and corrected by a subsequent uplink. There are also some faults that might appear to be CFEs, but do not fit the official definition. These faults include: pre-launch flight software or hardware faults including wear, tracking facility hardware failures, environmental faults including single event upsets, dust impacts, surface textures, etc. Any incident involving one of the factors may trigger the creation of an ISA, but will not be designated a CFE. ISAs are written for CFEs as for any other problem; however, additional data are required for closure of a CFE. The normal ISA process is used to manage the risk inherent in each CFE ISA and the MOAM ensures that they are properly closed and that residual risks have been documented.

A. Error Significance Model

Like ISAs, CFEs have also been examined. Detailed statistical analysis has revealed that primarily two operational factors drive CFE rates: the number of files radiated, and the level of novelty the flight team is experiencing as they build the uplink products. Novelty level changes when the flight team is engaged in a new mission phase which usually means that commanding has changed appreciably. There is low novelty when the team is doing the same type and level of activity for several months.

From these insights, an Error Significance Model (ESM) was developed to model the expected CFE rate based on these two factors. In the model, each uplink results in either an erroneous file execution or a successful file execution. Given the number of files and a novelty multiplier, the expected error rate can be calculated. One, two, and three sigma thresholds can be calculated and displayed, and the model can be used predictively if estimates of uplink file frequency are available.

It has been difficult for a MOAM to know if a given number of errors over a few months is cause for concern. This model allows the MOAM to understand the likelihood that the errors are within what is expected statistically. If the error frequency is higher than expected, the MOAM then works with the project to improve operational processes and/or conduct flight team training sessions. The ESM also allows the MOAM to anticipate upcoming periods of higher CFE occurrence, and to predict performance of future missions based on similar flying missions. The ESM allows MOAMs and project managers to understand the significance of a set of errors using statistics, rather than having to go with "gut feel." The ESM also allows MOAMs and project managers to set expectations with review boards about predicted numbers of errors and to potentially take steps to add resources around higher risk periods. An example of a project's ESM is shown in Figure 3 below.

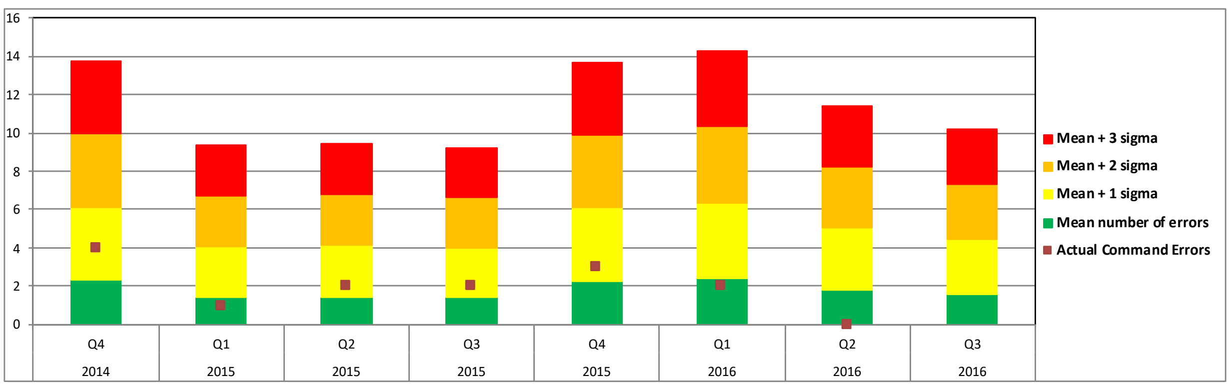

Fig. 3 Error Significance Model

Training Module 4 includes a presentation on managing command file errors, the Error Significance Model, and several current mission model examples. It also includes a discussion of the command error that caused the loss of the 1975 Viking 1 lander [4], and an example flight school refresher presentation that was given to the Dawn mission as a proactive step to avoid errors during the transition to Ceres operations.

In addition to tracking and working to prevent the types of errors that warrant CFEs and ISAs, the MOAM performs several other more common functions. They are covered in modules 5 through 10.

VIII. Module 5: Configuration Management Overview

Multi-mission Configuration Management is used by almost all JPL projects to document change requests (CR), waivers to command/sequence files, engineering documents, and mission/flight rules. The MOAM contributes to the CR and waiver processes by independently reviewing CRs and waivers for risk, and assessing any residual risk associated with the changes. In addition, the MOAM tracks change frequency and delves into periods of higher frequency to ensure that the project understands and accepts the risk implications.

Training Module 5 defines the various uses of change requests and waivers, defines capturing change impacts, and discusses change metrics and their meaning. Time permitting, the training also includes observing a project command approval meeting and a change board meeting.

IX. Module 6: Independent Risk Assessments

Each project maintains a list of mission risks. The MOAM reviews project risks on a regular basis and provides an independent assessment. At JPL, risks are managed in an institutional tool, written with wording per a NASA/JPL standard, and evaluated using a 5x5 likelihood vs. consequence matrix. The project and MOAM each maintain a formal risk list, but they are usually identical. Together they regularly review existing risks and consider if additional risks should be added. The MOAM may also perform detailed risk trade studies, as appropriate.

Training Module 6 includes a presentation on the Risk Assessment process and a demo of the JPL risk tool. It also includes examples of times when the Project and MOAM have disagreed on the recommended actions for a risk item [5, 6], and what was done to resolve the disagreement.

X. Module 7: Office of Safety and Mission Success Reporting

The Office of Safety and Mission Success (OSMS) requires formal reports for each project monthly. Each MOAM follows a standard template for these reports. Several areas in the template are only used if the project is at elevated risk levels. The overall intent of the report is to provide OSMS management with a thorough status of project activities and associated risks.

Training Module 7 includes a discussion of why this reporting is essential, and when to make an Independent Technical Authority report that may or may not conflict with the project's self-assessment. It then discusses how to gather the needed statistics and fill out the template.

XI. Module 8: Project Review Support

Projects hold readiness and risk reviews before important events. The MOAM contributes a presentation summarizing residual risk and flight team readiness to support the activity, leveraging information presented from past reviews. The presentation contains an assessment of the planning and execution of the event, the results of a review of open or related CFEs and ISAs, a review of formal risks, and notes any remaining areas of concern.

Training Module 8 includes a discussion of the various types of reviews and their requirements, as well as the MOAM's assessment of the risks. It also includes a presentation example from a Critical Event Readiness Review.

XII. Module 9: Institutional Waivers

All flight projects at JPL are required to comply with two institutional documents: the JPL Flight Project Practices, which describes how to operate a mission system, and the Design, Verification/Validation & Operations Principles for Flight Systems, which describes how to build a mission system. Both documents have a developmental focus, but each includes some operational requirements. In operations, waivers to these documents are sometimes necessary, particularly when problems with the flight system force the violation of a requirement. In these cases, the MOAM assists in the effort of writing and approving the waiver, or the MOAM may dissent from a proposed waiver.

Training Module 9 includes a definition of common situations where a waiver may be needed, how the creation and approval process is carried out, and the process for independently reporting a dissent. It also includes several waiver examples and discussion of a Voyager problem that led to the creation of one of the Design Principles.

XIII. Module 10: Anomaly Resolution

Another key part of the MOAM's job is to participate in Anomaly Resolution Teams and assist with the process. An anomaly is defined as (significant) abnormal behavior, out-of-specification performance, or unexplained occurrences in the flight system, ground data systems, or operational processes, procedures, and personnel. During anomalies, the MOAM is responsible for making certain that the flight team is on a safe path to resolving the anomaly. Special duties the MOAM may perform during an anomaly include helping to document the anomaly in an ISA, managing upward communication concerning the anomaly, and contacting off-project personnel that may be useful in analyzing and resolving the anomaly. In the event of significant spacecraft anomalies, failure review boards may be convened and mishap reports submitted.

Training Module 10 includes a presentation on the key points of anomaly communication and resolution, the types of anomaly support available from the other disciplines in the Office of Safety and Mission Success, and an example of the process for a criticality 1 anomaly.

The next two modules train MOAMs for responsibilities that are theirs on only a few specific missions. MOAMs, however, usually support 1-3 missions at a time, and can be called on to fill in for other MOAMs as necessary. For these reasons, cross-project familiarity with these other responsibilities is beneficial.

XIV. Module 11: Space Weather Reporting

Space weather can have a dramatic effect on spacecraft performance and communication, and some missions are particularly sensitive to geomagnetic and solar radiation storms. MOAMs may be called on to monitor solar activity for possible operational impacts and for anomaly investigations. This can begin with monitoring the space weather environment as part of the launch hold criteria, and continue post-launch.

Training Module 11 includes a presentation on the process of analyzing the space weather environment [7], a collection of URLs for available data sources, and data examples from noteworthy weather events. It also includes an example analysis and demonstration of an event that caused anomalies on both GRAIL spacecraft.

XV. Module 12: Mission Assurance in Rover Operations

Operating a rover at Mars has constraints not shared with orbiter and orbiter-like missions. These include weather and seasons, day/night power and thermal limitations, communication via relay with orbiting satellites or directly with earth to/from a rotating body, and 24- to 48-hour cycles from receiving decisional science data to the uplink of the next day's commanding. Each rover is also unique and sensitive to conditions, requiring a different level of involvement from mission assurance.

Training Module 12 walks through the daily process for the Curiosity mission including its communication architecture, strategic and tactical planning schedules, and daily reporting requirements. It also incorporates observation of an 8-hour tactical shift, time permitting.

XVI. Module 13: War Stories

The training module found most interesting by participants and trainers alike is the "war stories" session. A number of these stories were scattered throughout the previous modules to illustrate the topic of each module. Other stories present lessons learned in more complex situations such as major anomalies and mission losses, and are discussed near the end to pull all the material together. A variety of stories were prepared, with the expectation that the specific stories covered would be chosen depending on the composition of the class, current priorities, and availability of the storyteller. Though some of the stories were JPL-specific, most provide lessons applicable outside the mission assurance discipline [8-10].

XVII. Module 14: Case Study

The final module of the training provides an opportunity for trainees to act as a MOAM in a critical operations decision. For this case study, a risk trade is made for a decision to swap (or not) from redundant hardware back to primary hardware. The activity comes after a needed safe mode recovery is complete and before a critical orbit insertion. The results of the response to the original anomaly are provided along with any remaining risks. The trainees are given technical analyses of the risk drivers for each option, as well as concerns voiced by the stakeholders. The trainees perform a risk balance assessment and make a recommendation. A trainer, acting in the role of Project Manager, acknowledges the recommendation but makes a conflicting decision. Trainees then must create an Independent Technical Assessment to present to SMA management for the second, independent reporting path. To conclude this module, the trainer presents the actual events on which this study is based, discusses the decision, and summarizes the project's outcome. There is currently a single case study for the class. Others will be prepared for future sessions.

XVIII. Results and Looking Forward

The first offering of the MOAM class was held over several days between 17 July and 15 August 2017. Eight members of the MOAM group participated in the first offering, both as students and as speakers. Several other organizations sent trainees as well, including development mission assurance, sequencing, flight software, and mission operations system engineering. The next class offering is expected to take place in the fall of 2018. There have also been discussions with another NASA center about sharing training materials and possibly offering the JPL class at that center. The second of these discussions was held in April 2018.

There are also additional topics that may be added to future class offerings. Module 15, Mission Ending Events is under development now. It will discuss how missions come to their conclusion, whether via planned or unexpected events. There are currently 16 mission conclusions in the materials under development.

XIX. Conclusion

The mission operations assurance discipline grew out of the need to prevent operational errors, and evolved into what today is an independent technical authority dedicated to achieving mission success. The Mission Operations Assurance Manager (MOAM) role requires years of experience in operations, plus a comprehensive 14-module training program enabling the ability to identify, mitigate, and communicate project risks on multiple missions. The training program, developed to blend stand-up presentations with "war stories" from senior personnel and case studies to check understanding, has been successfully fielded for training new group members as well as cross-training operators and developers from other disciplines.

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